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Abstract

The time-sharing ability of 18 students was measured under 8 separate dual-task (double-stimulation) conditions. Three task characteristics -- input modality (auditory or visual), output modality (vocal or manual) and task difficulty (easy or difficult) -- were systematically varied across conditions in an effort to manipulate the nature of the specific time-sharing demands imposed. Each condition contained two of these characteristics in common with 3 of the remaining 7 conditions, one of the characteristics in common with 3 others, and none in common with the last condition. Time-sharing efficiency was found to correlate across conditions that impose similar processing demands on the individual, but not across conditions imposing relatively dissimilar demands. We conclude on this basis that time-sharing performance is largely determined by several poorly coorelated, task-specific subcapacities rather than by a single general capacity or ability.

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Is Time-Sharing a General Ability?

Human factors researchers have long assumed that a general time-sharing ability is influential in tasks such as piloting, driving and air-traffic control where high rates of information exchange are required between the operator and the environment. This belief has prompted a substantial research investment over the past three decades in efforts to develop measures of time-sharing that will predict performance in such tasks (e.g., Melton, 1947; Trankell, 1959; North and Gopher, 1976; and Damos, 1978). Much of this research has been based on a single-channel model of human information processing capacity. In this view, one's time-sharing ability is largely determined by the capacity of a single (central) processing structure through which most input-output transactions must be funneled. If this idea is correct, any measurement procedure that accurately reflects the individual's central processing capacity should be broadly predictive of time-sharing performance across a wide range of criterion situations.

An alternative view is possible, however, It could be that time-sharing performance is governed not by a single general capacity, but by several more specific subcapacities, each associated with a particular structure within the information-processing sequence. If such subcapacities were to some extent independent of one another and if their relative contributions to overall performance were to vary across time-sharing situations, the development of a single general predictor could prove a more complex task than has previously been assumed. These issues are examined in the experiment described in the present report.

Evidence consistent with the view that time-sharing is based upon several structure-specific subcapacities rather than upon a single general capacity appears in work recently completed at the University of Oregon. Some of

this work has been reported elsewhere (Hawkins, Church and deLemos, 1978). Subjects were tested in a variant of the double-stimulation paradigm in which the subject is required on each trial to make a speeded choice reaction to each of two distinct stimuli. The Task 1 stimulus (stimulus 1) appeared at the beginning of each trial, while the Task 2 stimulus (stimulus 2) appeared either simultaneously with stimulus 1 or following a variable delay ranging up to 1200 msec. Subjects were instructed to maintain a relatively stable mean reaction time (RT) to Task 1 across all interstimulus intervals, and were able to do so. We take this result to imply that the full force of the time-sharing demands imposed by the task combination at the shortest ISIs is manifested in performance on Task 2. Characteristic data patterns are illustrated in Figure 1.

Insert Fig. 1 about here

The increase in RT to Task 2 at the shortest ISIs is called the psychological refractory period (PRP) effect. The presence of a PRP effect implies an inability to completely time-share the processing demands of the two tasks. In some of the studies, stimulus 1 and stimulus 2 were either input through the same input modality (visual-visual) or through different modalities (auditory-visual). In other studies responses to the two stimuli were emitted through the same output modality (left hand manual-right hand manual) or through different modalities (vocal-right hand manual). In all studies two levels of Task 2 difficulty were presented and subjects were observed over several days of practice. Three of the findings of these studies are especially relevant to the present report.

First, we observed that when two simultaneous stimuli must share the same input modality (i.e. both stimuli were visual), time-sharing performance

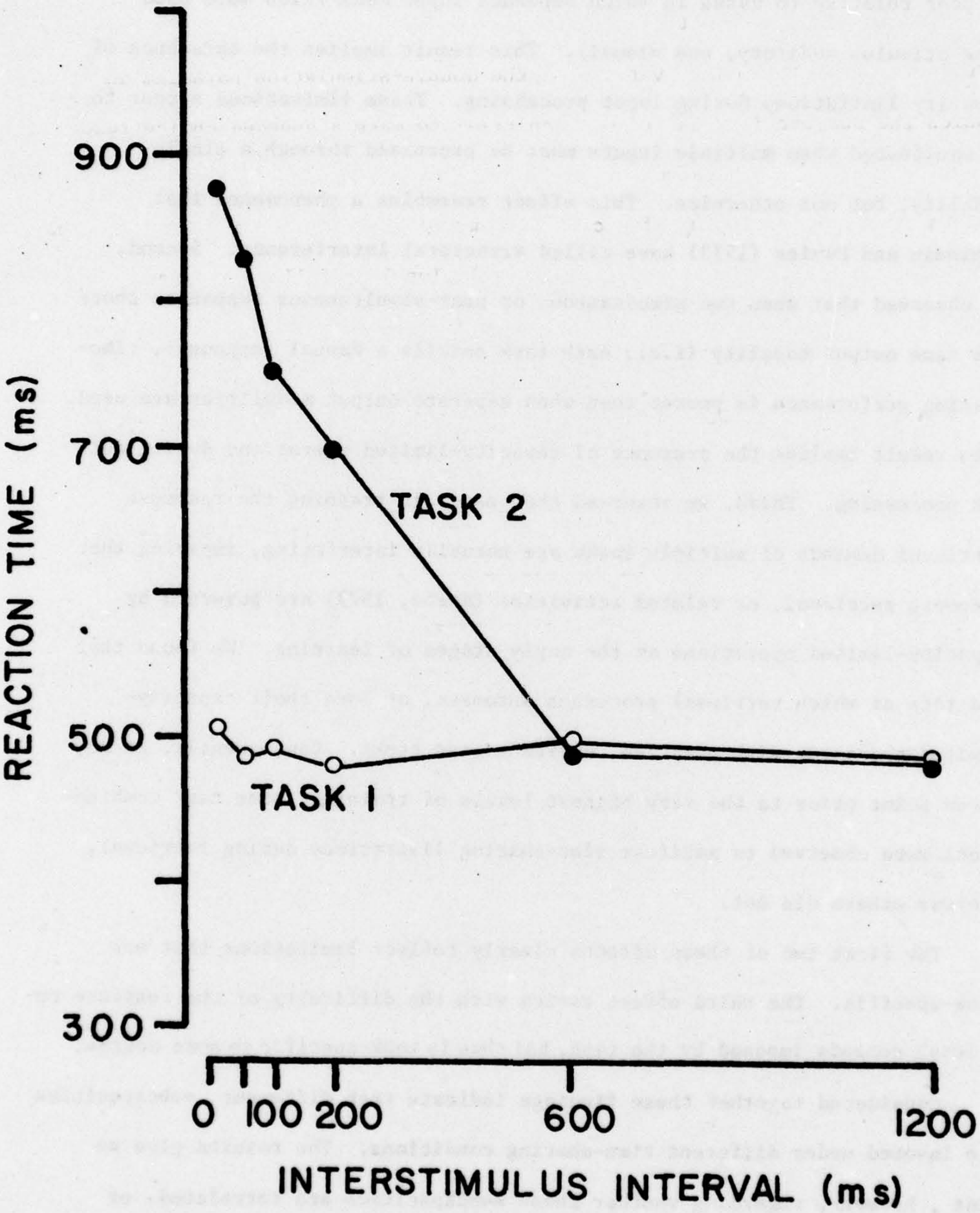

Figure 1. Task 1 and Task 2 Reaction Time under conditions of double stimulation as a function of interstimulus interval.

is poor relative to cases in which separate input modalities were used (one stimulus auditory, one visual). This result implies the existence of capacity limitations during input processing. These limitations appear to be manifested when multiple inputs must be processed through a single modality, but not otherwise. This effect resembles a phenomenon that Treisman and Davies (1973) have called structural interference. Second, we observed that when two simultaneous or near-simultaneous responses share the same output modality (i.e., each task entails a manual response), time-sharing performance is poorer than when separate output modalities are used. This result implies the presence of capacity-limited operations during output processing. Third, we observed that early in training the response retrieval demands of multiple tasks are mutually interfering, implying that response retrieval, or related activities (Keele, 1973) are governed by capacity-limited operations at the early stages of learning. We found that the rate at which retrieval processes automate, or lose their capacity-limited character with practice, varies across tasks. Consequently, at any given point prior to the very highest levels of training, some task combinations were observed to manifest time-sharing limitations during retrieval, whereas others did not.

The first two of these effects clearly reflect limitations that are task-specific. The third effect varies with the difficulty of the response retrieval demands imposed by the task, and thus is task-specific to some degree.

Considered together these findings indicate that different subcapacities are invoked under different time-sharing conditions. The results give no hint , however, regarding whether these subcapacities are correlated, or for that matter, whether the role they play in determining time-sharing performance is very important.

Recent work by Sverko (1977) raises the possibility that the subcapacities underlying time-sharing are both important and uncorrelated. Sverko tested 60 subjects on four information-processing tasks presented both singly and in all possible pair-wise combinations. The tasks were chosen because of their simplicity of administration and the fact that they presumably tap different psychomotor and mental functions. The tasks included rotary pursuit, visual choice reaction time, mental arithmetic and auditory discrimination. All task pairings were performed under instructions to assign equal priority to both tasks.

Sverko sought evidence for a general time-sharing ability using two separate procedures. First, the performance of subjects on each task under each condition (including both single and dual task conditions) was correlated with that on each task under all other conditions. The resulting intercorrelation matrix was then subjected to a principle component analysis. If a general time-sharing factor was manifested in the data five factors should have emerged, four task-specific factors and a general time-sharing factor. In fact, only four factors could be extracted, and these were clearly task-specific. Second, a total performance decrement score was calculated for each task pairing. This score is simply the sum of the proportionate performance loss on the two tasks when paired, relative to when they are carried out singly. The performance decrement score for each task pairing was then correlated with that for each other task pairing with the constraint that no common tasks appeared across pairings. The obtained correlation was essentially zero in all cases. While Sverko's procedure seems generally adequate, one potentially important problem exists with the study; although subjects were instructed to give equal emphasis to the two tasks time-shared under each condition, Sverko had no way to assess the extent to which this

instruction was followed. If performance on a given task does not vary as a linear function of the amount of one's capacity devoted to that task, and if the partition of capacity between tasks varied across conditions, this could have produced artifactually deflated correlations among conditions. Moreover, all of Sverko's tasks were continuous, and it is unknown how subjects interleaved the two tasks. Different tasks could have been interleaved differently by the same subject.

Accordingly, our purpose in the present study was to assess the relatedness of some of the time-sharing subcapacities we had previously identified, and to do so under conditions in which close experimental control can be exerted over the priorities assigned by subjects to component tasks. Subjects were tested under eight separate time-sharing conditions, some relatively similar to one another with respect to the specific subcapacities they are presumed to stress, and some relatively dissimilar. If time-sharing performance is dominated by a single general capacity or by correlated subcapacities, one would expect to see high correlations in time-sharing performance, both between conditions that are similar and those that are dissimilar. If performance is governed by uncorrelated subcapacities, correlations should occur between similar but not between dissimilar conditions.

METHOD

Subjects. The subjects were 10 men and 8 women drawn from the University of Oregon paid subject pool. None of the subjects had previously participated in a dual-task experiment. All reported normal or normal-corrected vision and none reported a hearing deficit.

Procedure. Subjects were tested for 1.5 to 2 h on each of two consecutive days. Practice was given on all experimental conditions at the

beginning of day 1. following practice on day 1 and beginning at the outset of day 2, subjects were tested for 84 trials under each of 8 time-sharing conditions. The order of the conditions was randomized across subjects and reversed across days within subjects.

Visual stimuli were displayed on a computer-controlled cathode ray tube situated in a small darkened subject cubicle. The subject was seated about 65 cm in front of the CRT display with the middle and index fingers of either the right hand or both hands (depending upon the condition) resting on piano-type response keys. Each trial began with the exposure of a fixation cross which remained in view in the center of the CRT screen for 500 msec. Under conditions in which two visual stimuli were presented, stimulus 1 appeared simultaneously with the offset of the fixation cross and .5 degrees to its left. Under conditions in which stimulus 1 was auditory, a pure 80 db(B) tone appeared binaurally over headphones, onsetting with offset of the fixation cross. Whether visual or auditory, stimulus 1 remained on for 500 msec. Following a stimulus onset asynchrony (SOA) of either 0, 50, 100, 200, 600, or 1200 msec, stimulus 2 appeared on the CRT screen .5 degrees to the right of the position that had been occupied by the fixation cross. When two visual stimuli were present, they subtended a visual angle of 1.6 degrees.

Under all conditions, instructions were to respond quickly and accurately and to treat Task 1 as primary. To facilitate the latter objective, verbal feedback concerning the pattern of Task 1 latencies was given following each trial block.

Time-sharing conditions. Eight time-sharing conditions were generated from the factorial combination of three binary variables. The three variables

were stimulus 1 modality (auditory or visual), response 1 modality (vocal or manual), and Task 2 difficulty (easy or difficult). The conditions are given in Table 1. Under all conditions Task 1 contained two stimulus

Insert Table 1 about here

alternatives, each requiring a unique response. Task 1 visual stimuli consisted of the upper-case letters H and N. The auditory Task 1 stimuli were an 800 and a 1200 hz tone. Under conditions in which Task 1 entailed a manual response, one stimulus required a response by the middle finger of the subject's left hand, and the other stimulus required a left-hand index finger response. Under vocal conditions, subjects responded with the word "RED" to one stimulus and with "GREEN" to the other. Response latencies under vocal conditions were measured by means of a voice-activated switching circuit.

Under all conditions stimulus 2 was visual and response 2 was manual. In the easy form of Task 2, stimuli were the digits 2 and 3. Subjects were instructed to respond with the index finger of the right hand when 2 appeared and with the middle finger of the same hand when 3 appeared. The difficult form of Task 2 consisted of two 4:1 S-R mappings: the digits 2, 5, 6 and 9 required a response by the index finger of the right hand and the digits 3, 4, 7 or 8 required a response by the middle finger of that hand.

Results and Discussion

Mean reaction time (RT) and proportion incorrect responses were calculated for each subject at each of the 6 SOAs for Tasks 1 and 2 under the 8 experimental conditions. The results, averaged across subjects, are given in Table 2. Two features of these data should be pointed out.

Table 1

Relations among the eight time-sharing conditions.

	Stimulus 1 - Visual, Stimulus 2 - Visual		Stimulus 1 - Auditory, Stimulus 2 - Visual	
	Easy Task 2 (1:1 S-R mappings)	Difficult Task 2 (4:1 S-R mappings)	Easy Task 2 (1:1 S-R mappings)	Difficult Task 2 (4:1 S-R mappings)
Response 1 - Vocal, Response 2 - Manual	VEV	VDV	AEV	ADV
Response 1 - Manual, Response 2 - Manual	VEM	VDM	AEM	ADM

Insert Table 2 about here

First, RT to Task 1 remained relatively invariant across SOAs. Second, a substantial increase in Task 2 latency between the 1200 msec and the 0 msec SOA (the PRP effect) was obtained under all conditions. These results indicate that we were successful in our effort to focus the effects of time-sharing onto Task 2 performance.

Two separate measures of time-sharing performance were used to evaluate the theoretical issues raised in the introduction. The first of these was the PRP effect (see above) which, we assumed, would vary as the inverse of the individual's time-sharing effectiveness. Correlations in PRP magnitude were calculated between all possible pairings of the 8 conditions. These correlations, and split-half reliabilities for all conditions, appear in Table 3.

Insert Table 3 about here

The correlations are organized according to the number and type of attributes common to the two conditions correlated. It is clear from the table that substantially high correlations in PRP magnitude occur across these time-sharing conditions, even between those formally sharing no common attributes. These results indicate that PRP magnitude was influenced by a common factor across the 8 conditions. However, is time-sharing the common factor? It could be that the longer a person's RT to Task 1 the longer it will tend to be before full attention can be turned to processing stimulus 2, and hence the greater the delay in responding to that stimulus.

Table 2(a)

Mean reaction time and proportion errors (in parentheses) for stimulus 1 averaged across subjects at each SOA under each of the 8 time-sharing conditions.

Stimulus 1

Stimulus onset asynchrony (msec)

Condition	0	50	100	200	600	1200
AEM	631	627	630	627	623	632
	(.049)	(.042)	(.064)	(.046)	(.032)	(.028)
ADM	640	654	638	626	615	632
	(.038)	(.052)	(.028)	(.046)	(.028)	(.036)
VEM	538	542	533	526	528	532
	(.050)	(.042)	(.030)	(.042)	(.028)	(.050)
VDM	556	557	543	545	550	552
	(.036)	(.028)	(.030)	(.034)	(.028)	(.028)
AEV[a]	738	727	731	727	731	720
ADV[a]	761	775	707	779	760	762
VEV[a]	640	665	647	643	625	642
VDV[a]	652	648	653	645	667	662

[a]Vocal trials were spot monitored for errors during practice. Error rate was found to be negligible or nonexistent for all subjects at this time.

Table 2(b)

Mean reaction time and proportion errors (in parentheses) for stimulus 2, averaged across subjects at each SOA under each of the 8 time-sharing conditions.

Stimulus 2

Stimulus Onset Asynchrony (msec)

Condition	0	50	100	200	600	1200
AEM	1050	1010	950	840	521	456
	(.028)	(.034)	(.050)	(.028)	(.036)	(.028)
ADM	1085	1041	982	896	776	636
	(.076)	(.070)	(.071)	(.083)	(.083)	(.095)
VEM	781	751	703	666	469	473
	(.048)	(.040)	(.030)	(.048)	(.064)	(.024)
VDM	979	925	876	750	649	594
	(.091)	(.093)	(.058)	(.099)	(.077)	(.056)
AEV	985	925	842	726	584	522
	(.051)	(.056)	(.048)	(.050)	(.080)	(.056)
ADV	1059	1031	980	927	717	667
	(.098)	(.065)	(.079)	(.078)	(.085)	(.087)
VEV	938	926	825	731	533	457
	(.073)	(.070)	(.071)	(.063)	(.050)	(.058)
VDV	1051	1022	961	855	691	605
	(.106)	(.105)	(.109)	(.091)	(.113)	(.085)

Table 3

Correlation in the magnitude of the psychological refractory period (PRP) effect as a function of the number of characteristics shared by two conditions. Condition codes and split-half reliabilities are given in the top portion of the table. A correlation coefficient of .40 is significant at the .05 level.

Code	Condition	Reliability	Code	Condition	Reliability
1	AEM	.927	5	VEM	.960
2	ADM	.945	6	VDM	.849
3	AEV	.921	7	VEV	.912
4	ADV	.967	8	VDV	.765

No Common Characteristic

r_{1-8}	= .691
r_{2-7}	= .494
r_{3-6}	= .709
r_{4-5}	= .435
Mean r^{a}	= .592

One Common Characteristic

	Input		Output		Difficulty
r_{1-4}	= .777	r_{1-6}	= .388	r_{1-7}	= .499
r_{2-3}	= .744	r_{2-5}	= .386	r_{2-8}	= .416
r_{5-8}	= .396	r_{3-8}	= .697	r_{3-5}	= .692
r_{6-7}	= .391	r_{4-7}	= .428	r_{4-6}	= .522
Mean r^{a}	= .608		.488		.540

Two Common Characteristics

	Input-Output		Input-Difficulty		Output-Difficulty
r_{1-2}	= .624	r_{1-3}	= .713	r_{1-5}	= .462
r_{3-4}	= .712	r_{2-4}	= .669	r_{2-6}	= .499
r_{5-6}	= .777	r_{5-6}	= .632	r_{3-7}	= .720
r_{7-8}	= .522	r_{6-8}	= .340	r_{4-8}	= .440
Mean r^{a}	= .659		.568		.562

[a]Mean r was obtained by transforming each r to z, calculating mean z, then transforming back to r.

In other words, the delay in stimulus 2 processing which constitutes the PRP effect could be determined in large measure by how slow the person is to Task 1.

We evaluated this possibility by correlating the magnitude of the PRP effect with Task 1 latency at the shortest SOA. A correlation of .815 was obtained, indicating that those who were fastest on Task 1 indeed showed the smallest interference effect on Task 2. This result is consistent with the idea that the high correlations shown in Table 3 are an artifact of overall quickness. The possibility remains, however, that quick individuals are also good at time-sharing. To separate these two possibilities we developed a measure of time-sharing effectiveness that is not confounded by the individual's overall quickness. The measure, time-sharing efficiency (e_{ts}), is defined as the amount of Task 2 processing, in msec, per msec of Task 1 processing. That is,

$$e_{ts} = \frac{RT_{2_{1200}} - (RT_{2_0} - RT_{1_0})}{RT_{1_0}},$$

where RT_{1_0} is the response latency to Task 1 at the 0 SOA, $RT_{2_{1200}}$ is the response latency to Task 2 at the 1200 msec SOA, and RT_{2_0} is the Task 2 latency at 0 SOA. Were no PRP effect present -- that is, should RT_2 not elevate at the shortest asynchrony -- the value of e_{ts} would be 1.00. If the PRP effect were to equal RT_{1_0}, as though no Task 2 processing took place prior to response 1, the value of e_{ts} would be .00. The measure will show a negative value should the PRP effect exceed Task 1 latency.

In an initial attempt to validate e_{ts} as a measure of time-sharing effectiveness, we looked at its behavior across conditions that should predictably differ in time-sharing difficulty. Three comparisons were of special interest: (1) between visual-visual and auditory-visual conditions;

(2) between manual-manual and vocal-manual conditions; and (3) between conditions containing the easier and those containing the more difficult Task 2. Table 4 shows the results of this analysis. Each e_{ts} entry

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Insert Table 4 about here

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represents the mean of four conditions: for instance, the visual-visual conditions consisted of VEV, VDV, VEM and VDM. The obtained pattern of results is consistent with what one would expect if e_{ts} is measuring time-sharing effectiveness. Efficiency is slightly lower when the same input modality is used by both tasks than when different modalities are used (c.f. Treisman, 1969; Hawkins, Church & deLemos, 1978), and is slightly lower when the same output modality is used by both tasks than when separate modalities are used (c.f. McLeod, 1978). Efficiency is also lower when the easier form of Task 2 is used. This counter-intuitive result is expected on the basis of prior data (Karlin and Kestenbaum, 1969; Hawkins, Church & deLemos, 1978), which indicate that an easy second task shows a larger PRP effect than does a difficult one. Data of this form have been interpreted by Keele (1973) through the assumption that much of the increased reaction time which the difficulty of the second task induces is due to processes that are time-consuming but <u>automatic</u>. As a result, the longer-lasting task is actually better able to be time-shared.

Having established that e_{ts} exhibits a measure of construct validity, we then determined the extent to which its value correlates across the 8 conditions of the experiment. These correlations and split-half reliabilities for conditions are given in Table 5. It is readily apparent that the

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Insert Table 5 about here

Table 4

Time-sharing efficiency as a function of input, output and difficulty level.

Condition	e_{ts}	Significance Level
Manual (Task 1)	.253	$p < .02$
Vocal (Task 1)	.356	
Visual (Task 1)	.281	$p < .10$
Auditory (Task 1)	.328	
Easy (Task 2)	.257	$p < .05$
Difficult (Task 2)	.352	

Table 5

Correlation in time-sharing efficiency, e_{ts}, as a function of the number of characteristics shared by two conditions. Condition codes and split-half reliabilities are given in the top portion of the table. A correlation coefficient of .40 is significant at the .05 level.

Code	Condition	Reliability	Code	Condition	Reliability
1	AEM	.855	5	VEM	.883
2	ADM	.668	6	VDM	.789
3	AEV	.892	7	VEV	.866
4	ADV	.927	8	VDV	.663

No Common Characteristic

r_{1-8}	= .087
r_{2-7}	= .205
r_{3-6}	= .147
r_{4-5}	= .181
Mean r^a	= .154

One Common Characteristic

	Input	Output	Difficulty
	r_{1-4} = .654	r_{1-6} = .417	r_{1-7} = .184
	r_{2-3} = .483	r_{2-5} = .338	r_{2-8} = .192
	r_{5-8} = .129	r_{3-8} = .180	r_{3-5} = .357
	r_{6-7} = .520	r_{4-7} = .097	r_{4-6} = .365
Mean r^a	= .465	.263	.276

Two Common Characteristics

	Input-Output	Input-Difficulty	Output-Difficulty
	r_{1-2} = .738	r_{1-3} = .564	r_{1-5} = .575
	r_{3-4} = .411	r_{2-4} = .605	r_{2-6} = .423
	r_{5-6} = .739	r_{5-7} = .520	r_{3-7} = .320
	r_{7-8} = .520	r_{6-8} = .079	r_{408} = .239
Mean r^a	= .621	.461	.424

[a]Mean r obtained by transforming r to z, calculating mean z, then transforming back to r.

measure correlates reasonably well across many of the conditions that impose the same types of time-sharing demands. However, when different demands are imposed by a pair of conditions, little or no correlation is observed.

We interpret these results as demonstrating that time-sharing performance is governed by a number of poorly-correlated, task-specific subcapacities, rather than by a single, general capacity or by a set of correlated subcapacities. An individual who performs well in one time-sharing situation will not necessarily perform well in another unless the two situations stress the same set of subcapacities.

How well does this conclusion accord with the literature on time-sharing? While reports supposing the existence of a general time-sharing ability are numerous, we are aware of only three studies in which the supposition has actually been tested. One of these was the Sverko (1977) study, which we have discussed previously. A second was reported over 60 years ago by McQueen (1917). McQueen tested elementary school children on a variety of psychomotor and cognitive tasks, presented both singly and concurrently. Using correlational methods, McQueen was unable to find any evidence whatsoever for a general ability to time share, or as he put it, to "distribute attention" across multiple tasks. The third study was by Jennings and Chiles (1977) whose results have been interpreted as favoring the existence of a general time-sharing ability. A close examination of their results, however, indicates that while they may have identified a time-sharing factor, this factor is <u>not</u> general across the tasks they studied. Rather, what they have uncovered appears to be a task-specific subability, perhaps along the lines of those evidenced in the present study. The procedure used by Jennings and Chiles, like that of Sverko, was to factor analyze

the results of a set of tasks when these were carried out singly and in combination. One of the factors extracted from the analysis showed high loadings for two different low-signal density, visual monitoring tasks when these were performed concurrently with other tasks, but not when they were carried out singly. However, because no other tasks, including 2-dimensional tracking, loaded on this factor under concurrent conditions, the factor is clearly quite specific to a particular class of monitoring tasks.

Data that seem to provide at least indirect support for the idea of a general time-sharing ability have appeared in several studies examining the relationship between measured time-sharing and piloting performance (Melton, 1947; Trankell, 1959; Gopher and North, 1976; Damos, 1978). Even though the nature of the time-sharing predictor tasks differed substantially across these four studies, all obtained statistically reliable correlations. However, it is understandable that these results might be obtained even though time-sharing is not a general ability factor. Piloting is a highly complex task in which information input through visual, auditory, tactile and vestibular channels must be transformed, integrated and acted upon through a variety of output modalities. Consequently, at one time or another piloting probably taxes, and is influenced by, most of the subcapacities implicated in time-sharing. By the same reasoning, one would not expect that correlations between any single time-sharing measure and piloting performance would be substantial (and indeed they are not) for no single measure is apt to reflect all the subcapacities relevant to piloting. Thus a potentially useful selection strategy is to test candidates on a battery of tasks tapping a variety of time-sharing subcapacities. A multiple regression analysis of the data obtained from such an effort could both enhance the predictive

power of one's measurement procedures and lend insights into the relative contributions of the various time-sharing subcapacities in determining performance in the criterion situation.

Reference Note

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